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EFFECT OF A ZERO G ENVIRONMENT ON FLAMMABILITY LIMITS AS DETERMINED USING A STANDARD FLAMMABILITY TUBE APPARATUS

Roger A. Strehlow and David L. Reuss

SUMMARY

This report contains a justification for and the results of a feasibility study of a program to study flammability limits at zero g in Space Lab. The conclusions of the report are that there is a very good justification for both studying flammability limits and the flow associated with lean limit flames under zero g conditions and for performing such studies in the Space Lab environment. The feasibility study shows that the only technique that one can use to determine the important flow parameters associated with lean limit flames is the Space Lab facility. It is the only feasible technique because of the delicate nature of the equipment which must be used to make such a determination and because observational times of more than 20 seconds are required in order to properly determine lean limit flammability. Additionally, the report makes some recommendations for the conceptual design of the Space Lab facility so that it can accommodate the lean limit flammability tube experiment.

I. INTRODUCTION

Historically, the determination of flammability limits has been important for both the determination of safe operating conditions in industrial environments and for the design of more effective burners for combustion processes. Recently, lean limit flammability has taken on added importance because of the emphasis on developing engines which produce low levels of pollutants in their exhausts. Lean limit combustion is very attractive for two reasons. On the lean side, carbon monoxide is not produced in any great quantity, and, because of the low flame temperatures, nitric oxide levels are also low. Thus, there has been a considerable resurgence of research relative to the mechanism of lean limit flammability.

It is well known that the actual lean limits as determined experimentally are very dependent not only on the apparatus that is used for the

determination but also on the presence of the earth's gravitational field. It is true, in fact, that upward and downward propagation limits are markedly different for many fuels. Unfortunately, there is neither a good experimental explanation for why this is so, nor are there any realistic theoretical explanations for the observed experimental effects.

This report contains a justification for studying in detail the flows associated with a lean limit flame in a particular geometry and for doing this experiment in space. It also looks at the question of the feasibility of performing this particular experiment in space and makes some recommendations as to conceptual design of the Space Lab facility that will be required to house the preferred apparatus. A conceptual design for such a facility is contained in reference 1.

II. JUSTIFICATION

There are many techniques that one can use to determine a flammability limit. However, the technique that should be used for a study of this type has one primary requirement, that is, that the geometry of the apparatus and the flame system in the apparatus be such a type that is most tractable analytically. Additionally, we are looking for an experimental technique in which buoyancy has a well documented effect. Of the many geometries that are available for flammability studies, the standard flammability tube apparatus best meets the above requirements. An upward propagating flame in such an apparatus has a two-dimensional, steady configuration when one is traveling in a coordinate system at the flame's speed up the tube and therefore is by far the most tractable system available under limit conditions. Additionally, the zero g drops that were performed under this grant have shown that the flame retains a very similar shape and a constant propagation speed under zero g conditions (albeit, much less than that observed under 1-g conditions) and therefore that the zero g flame would also be tractable mathematically.

It is important to perform this experiment under zero g conditions because buoyancy forces markedly affect these very weak limit flames on earth. Since we have developed the techniques to measure the velocity field associated with these flames, the changes in such a velocity field that one would

observe between normal and zero g conditions are very important to developing an analytic understanding of why these flames extinguish. Also, it is very important to determine how the lack of gravity affects the actual limit composition of the combustible mixture.

A more detailed description of the different types of apparatus used for measuring the flammability limits is given in the third chapter of the microfiche supplement, followed by a discussion of the reasons for choosing the standard flammability limit tube for this study. In the fourth chapter of the microfiche supplement a critique of the theories predicting the occurrence of the flammability limits is presented.

The experiments that we propose to do are necessary if one is to have any hope of preparing an analytic representation of these new limit flames. The experiments involve using an extremely delicate instrument, a laser Doppler anemometer (LDA), which could not be deployed safely in any of the other current experiments that produce short-term zero g. The instrument is extremely expensive and one time use would be prohibitive. Additionally, the experiments that were performed in the drop tower at NASA Lewis Laboratory have shown quite definitely that one will need at least 20 to 30 seconds to determine a lean limit for the methane-air system under zero g conditions. This much time is just not available in any of the other zero g facilities in which, from a practical point of view, this could be done.

III. FEASIBILITY

A. The Issues

The following issues have been identified as important to the question of the feasibility of placing a standard flammability tube apparatus in Space Lab for detailed studies under zero g conditions. These are:

1. Time required for a single zero g test.
2. Size of apparatus required.
3. Ignition system.
4. Particle seeding system.
5. Feasibility of using a LDA in a standard flammability limit tube.
6. Feasibility of using holographic interferometry for measuring the density distribution.

7. Gas requirements.
8. How flammability limits change in the zero g environment.
9. How flame shape and velocities change in the zero g environment.

B. Results

1. As applied to the feasibility issues.

a. Time required for a single zero g test.

The actual test time will be somewhat less than 1/2 minute. However, the tube must be prepared between testing and this will take additional time. Before each test, the tube should be swabbed with an ethyl alcohol-soaked swab. Failure to swab the tube before each test will result in an increase in the flame propagation velocity (refer to Chapter 5 in the microfiche supplement). Swabbing is also necessary to prevent particle accumulation on the tube walls during LDA tests. After the tube has been swabbed, a flow of air or vacuum evacuation must be used to dry the tube. At this point the test mixture should be introduced and again approximately 10 tube volumes should be used to ensure the desired composition is attained. For this purpose both ends of the tube will be closed except for small ports. At one end the port will be connected to the gas supply system and at the other end the port will be connected to an exhausting system such that the excess combustible mixture or the ethyl alcohol-air mixtures do not contaminate the combustion facility or Space Lab environment.

It is felt that the combustion facility's volume is sufficiently large that four or five flammability tests can be run in the volume before the air in the volume should be displaced with fresh air. In this regard, the question as to whether the facility has to be opened between each run is still not finalized. More than one run could probably be made without opening the combustion facility to the Space Lab environment if all functions necessary for the test sequence could be implemented remotely. This would require a repetitive igniter, remote control of flow settings and apparatus positioning, and an automatic swabbing mechanism. In this case, a run would consist of the following sequence of events:

i. Both ends of the tube open - automatic clean ethyl alcohol swab pulled or pushed through the tube.

ii. Both ends of the tube open, one connected to supply system, one to exhaust system; ten changes of air through the tube to dry the tube, or evacuate.

iii. Ten changes of methane-air mixture of desired composition to refill the tube.

iv. Vent to outside closed; small quantity of methane injected near igniter cell; wait for 2 or 3 seconds for diffusion to occur (this can be calculated); igniter end opened to combustion facility and tube fired.

v. Observation of flame either with cameras, the eye, holographic or LDA techniques.

vi. Repeat the cycle.

Total elapsed time approximately 10 min/run. If the tube can not be swabbed remotely, it is estimated that an additional 10 min/run would be required.

b. Size of apparatus required.

The standard flammability limit tube is 51 mm internal diameter and 1.8 meters long. For this facility you would have to use a tube which would be only 1 meter long but of the same internal diameter as the standard flammability tube. The combustion experiment would fit nicely into the combustion facility chamber. The LDA and the cameras to photograph the events must be external to the system but there is space provided for them. This will be discussed in more detail later.

c. Ignition system.

An ignition system was developed which involved injecting methane near the location of the ignition wire and coating the ignition wire with a nitrocellulose film. If repetitive operations are desired, coated wires could not be used unless some mechanism was avilable to replace one wire with another by remote control. It is felt, however, that with methane injection near the igniter a properly designed uncoated wire would probably suffice as an ignition source. In this regard, a glow wire seems to be the most appropriate ignition source for this experiment.

d. Particle-seeding system.

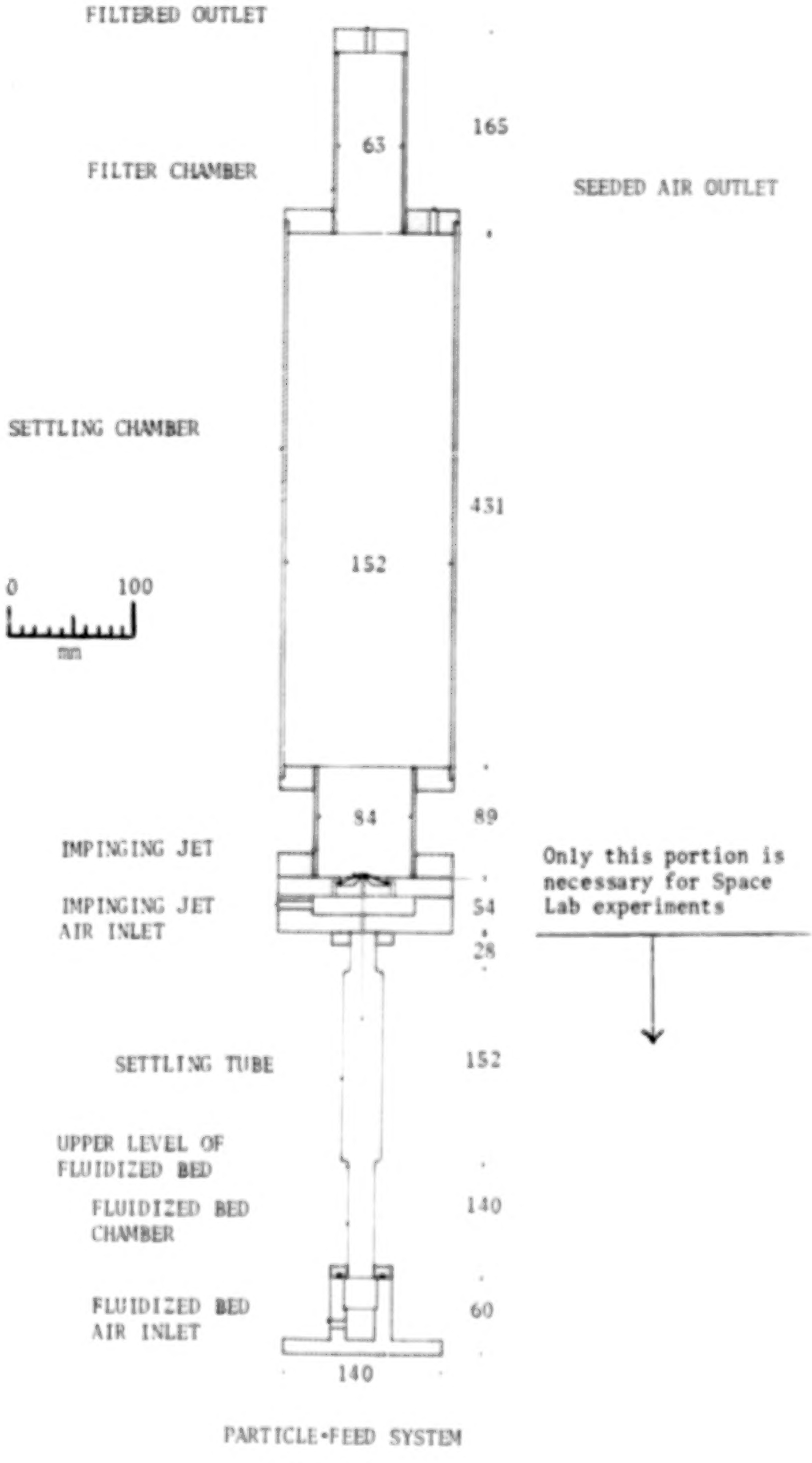
The particle-seeding system that was developed during the experiment feasibility study is not a viable system under zero g conditions because it relies on gravity to develop a seeded gas flow. Figure 1 shows an illustration of the particle-feed system used in 1-g. For the low air flow rates used in the 1-g study, the impinging air jets were actually not needed. Therefore, only the "fluidized bed" and "settling tube" portions of the feed system will be needed in the Space Lab tests if similar flow rates are used while filling the SFLT. Figure 2 shows a proposed particle-feed system for zero g conditions. In this apparatus a tube is rotated at such a velocity that the fluidized bed at the terminus of the tube experiences essentially a 1-g force.

e. Feasibility of using a LDA in a standard flammability tube.

Figure 3 is a sketch of a forward scattering LDA system which could be intalled to surround the combustion chamber in the combustion facility rack. There is sufficient space to house such an LDA system in this facility. It appears that there is no question but that this LDA design will work under Space Lab conditions. The feasibility of using an LDA system in a SFLT has been shown in the ground-based experiments described in the microfiche supplement.

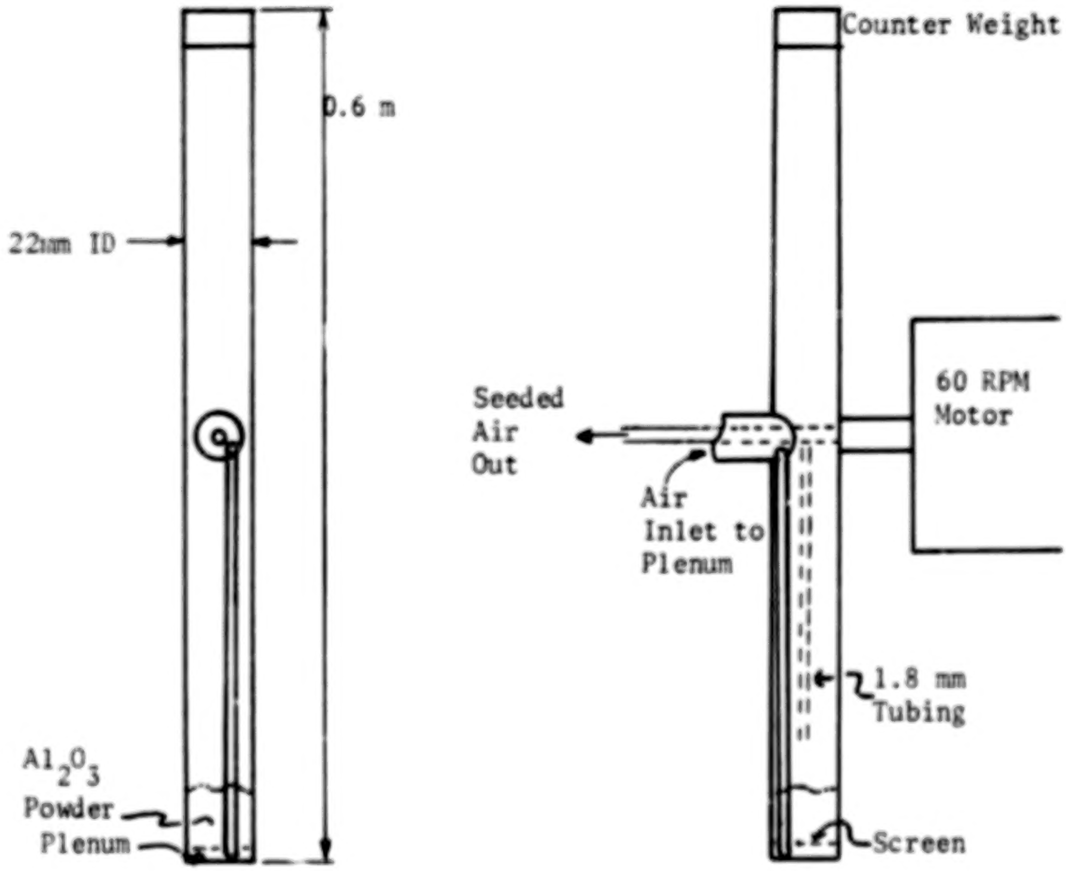
f. Feasibility of using holographic interferometry for measuring the density distribution in a standard flammability limit tube.

It appears that, at the present time, it is not feasible to place a holographic interferometer on the Space Lab for combustion studies. The reason for this is that the present combustion facility does not have the proper dimensions for interfacing with a holographic interferometer. However, a holographic interferometer suitable for studies in a standard flammbility limit tube could be constructed in the room available in a double rack. In addition, with the development of light-weight, compact and internally damped optical tables, the question of vibrational stability is not a problem. The nearly ideal low-g environment of Space Lab would make vibration even less of a problem since nonrigid table supports could be utilized. If the flammability tube is mounted directly to the optical table and the table is



PARTICLE-FEED SYSTEM

Figure 1



Fluidized Bed Particle Seeding System
for Use in 0-G Environment

Figure 2

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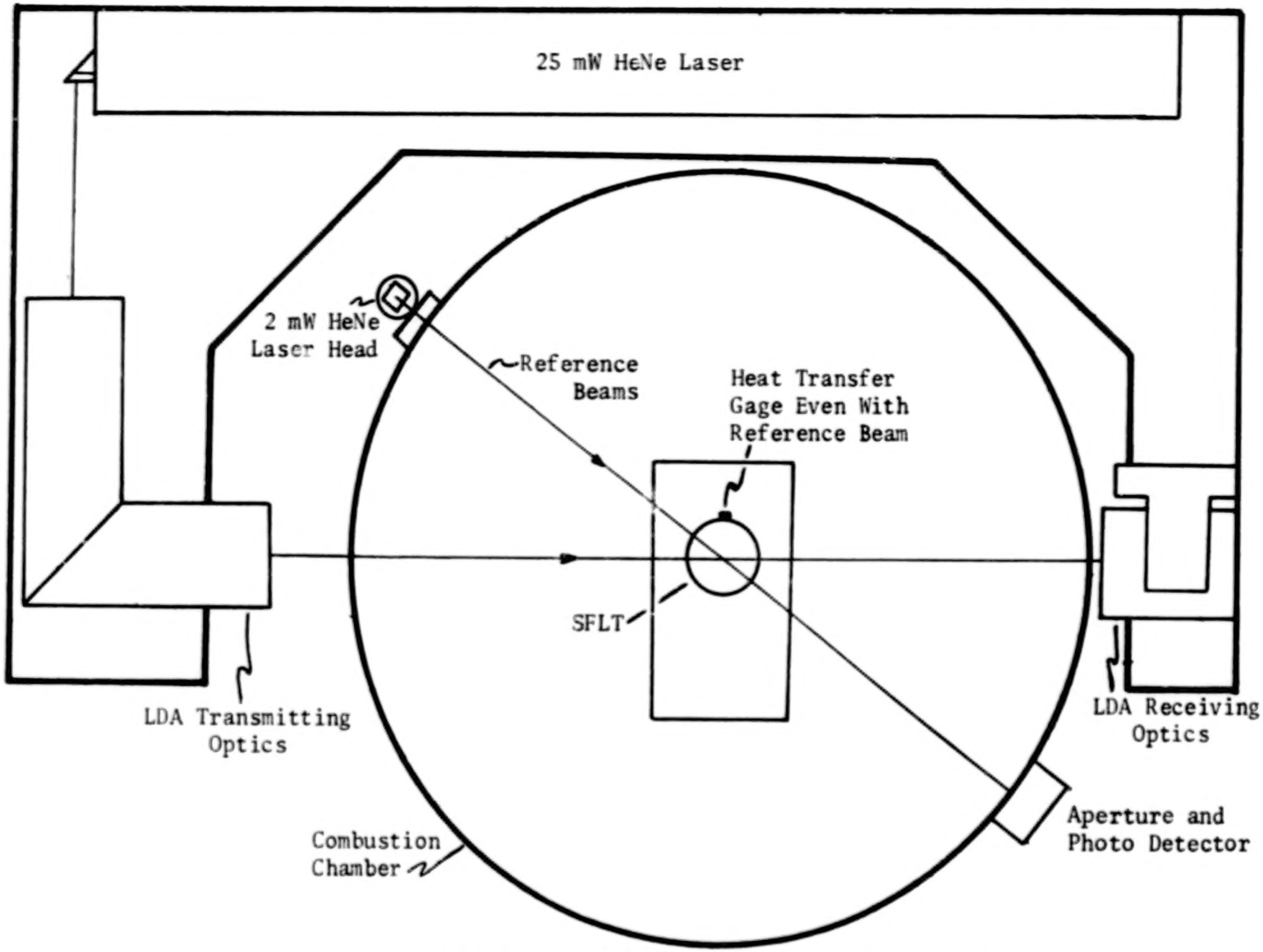


Illustration of Proposed Experimental Equipment
Top View

Figure 3

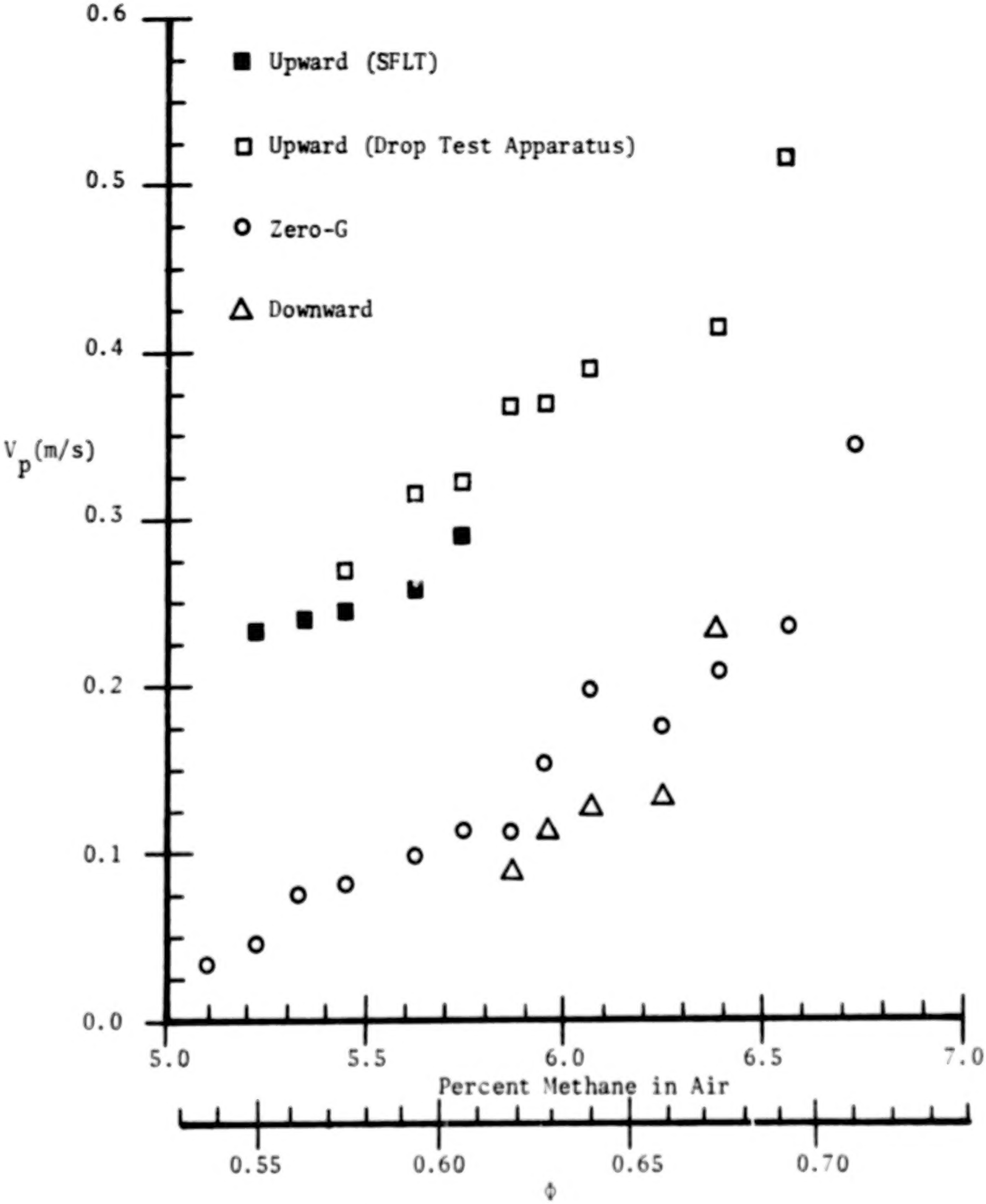
magnetically positioned, the only external force available to disturb the optical system would be through the flexible electrical and gas feed umbilicals. Since internal excitation of the optical system is the only problem, this external force would be negligible when compared to that in an on-earth laboratory. On board, photo processing of the hologram could be accomplished by a commercially available automatic processor while the plate is in place. Because the instrument is so useful for this and other studies (not only combustion studies), it would be highly desirable to investigate in greater depth the feasibility of constructing a holographic interferometer for use in space on some of the future Space Lab missions.

g. Gas requirements.

Assuming that the tube is cleaned by displacing with 10 volumes of clean air and filled by displacing with 10 volumes of the appropriate methane-air mixture, one would need approximately 40 liters of air at standard conditions and 2 liters of methane per test. After approximately 5 tests, one would have to purge and refill the combustion chamber itself in all probability. The air requirement that is given above is only to purge and fill the flammability tube itself.

h. How flammability limit changes in the zero g environment.

Figure 4 contains data that were obtained using the 2.3 second zero g drop tower facility at the Lewis Research Center. The major purpose of this work was to determine the leanest mixture composition that would allow flame propagation in a 0-g environment and the character of the flame near that limit. Due to the short amount of 0-g time available (2.3 s/test) the flame could not propagate the full length as leaner mixtures were used and the flame propagation velocities were below 10 cm/sec. However, homogeneous tests were made progressively leaner until the flame was observed to extinguish during the test. The results of these tests indicated that the flame in the 5.20% mixture attained a steady propagation velocity of approximately 4 cm/s. At a mixture of 5.1% methane, the flame did not obtain steady state in the available test time. However, with mixtures containing 4.98% methane, the flame always extinguished. It is tentatively concluded that the 0-g lean limit mixture composition is about 5.20%. However, longer 0-g times



Flame Front Propagation Velocity
of Lean Methane-Air Flames
in 0-G and 1-G

Figure 4

must be available in order to verify this conclusion.

i. How flame shape and velocity changes under the zero g environment.

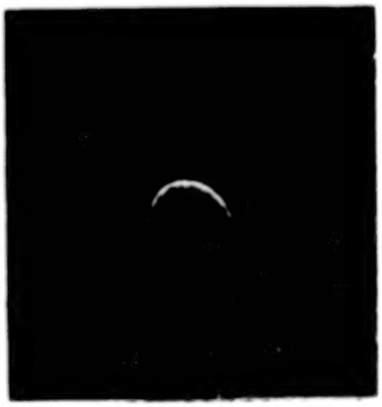
Figure 5 shows some flame photographs taken at the zero g facility at Lewis Research Center. The flame is seen to look somewhat like an upward propagating flame only with a much shorter skirt. Since the flame shape is a manifestation of the flow field and the flow field is affected by the presence or absence of gravity, a change in shape was expected. However, the fact that the highly curved 0-g flame and the flat downward 1-g flame propagate at about the same velocity for a given mixture (see Fig. 4) was not expected based on present conceptual models of flame propagation. The presence of this anomaly is just one more incentive for studying the velocity and density distributions in zero gravity.

2. Original scientific accomplishments.

The experiments performed during the feasibility study show that a laser Doppler anemometer can be used with a standard flammability tube apparatus and also show that the motion of the laser Doppler test region due to refractive indices changes associated with the flame passage must be interpreted in order to properly evaluate LDA signal records. The LDA results showed that, as viewed in the stationary (laboratory) coordinate, on the center line the motion ahead of an upward propagating flame is upward and away from the flame; the motion inside the flame sheet is everywhere downward; near the walls the primary motion ahead of the flame is downward; and at about the edge of the flame's skirt the downward velocity of the hot product gases near the wall is higher than the downward velocity in the central region of the flow. The axial velocity distribution, as viewed in the flame's coordinates, are presented in Fig. 6. In this coordinate system the velocity distribution is steady. The solid line is the position of the luminous flame zone. The arrows represent the magnitude of the axial velocity at their respective origin. One important result is the fact that unlike a steady 1-D flame, the velocity along the centerline first decreases and then increases as a fluid element passes through the flame. Secondly, the fluid motion occurs 15 mm upstream from the luminous flame zone. These

1-G 0-G 1-G

5.87%

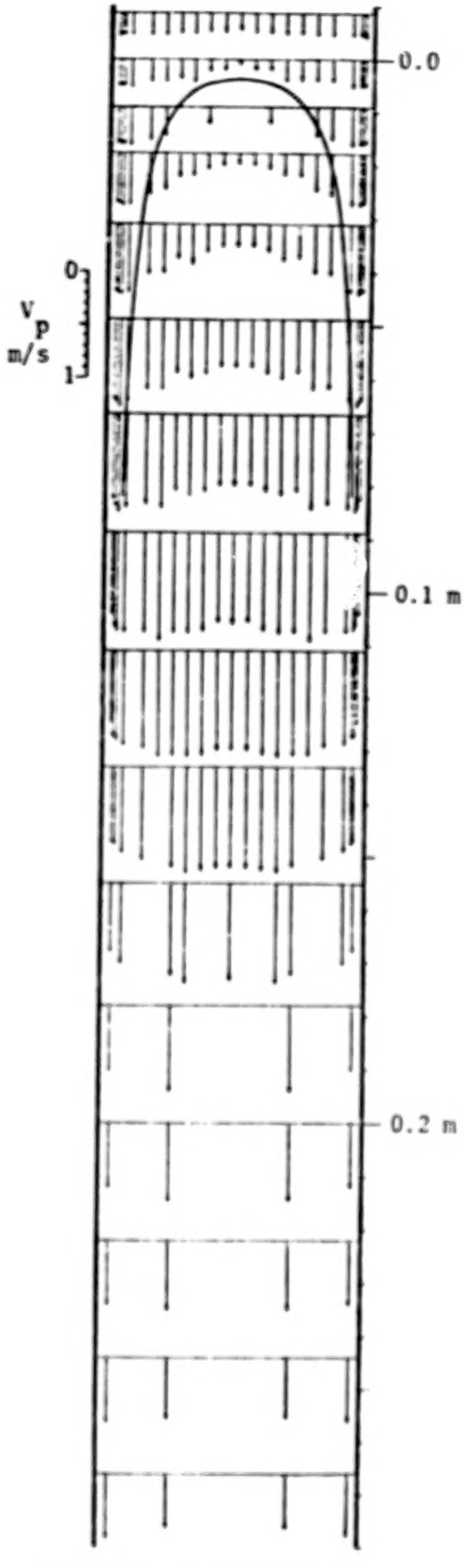


0-G

5.33%

Photographs of Lean Methane-Air Flames

Figure 5



Axial Velocity Distribution
In Coordinates that Move with the Flame
Figure 6

results are all new and their observation should ultimately contribute to a better understanding of the mechanism of lean limit extinction. See the microfiche supplement for a more detailed discussion.

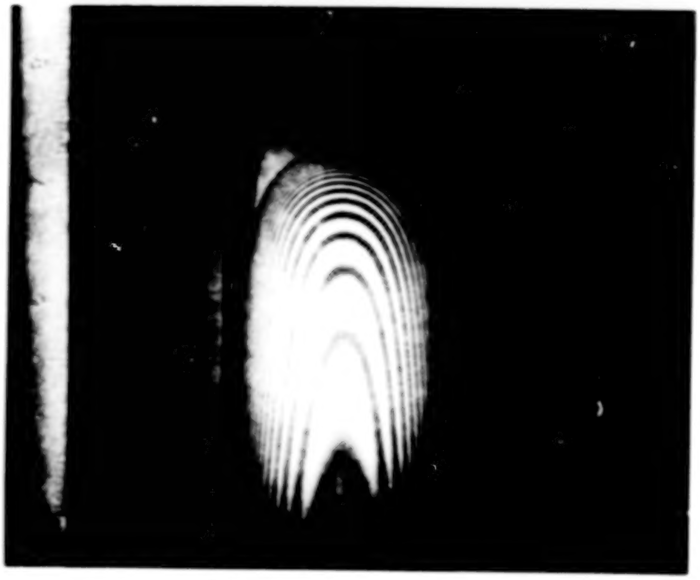
Holographic interferometric records were obtained of both the lean limit flame and the hot bubble that exists just after flame extinction. It was found that the inversion technique used to determine temperature distribution from these records was inaccurate primarily because the exposure time using our laser was such that the flame moved a considerable distance during exposure when compared to the width between the fringes that were produced on the interferograms. Two of these records are shown in Figs. 7 and 8. Calculation of the temperature distribution from these interferograms was fruitless due to the inadequacy of the equipment available for the feasibility study. A more powerful laser than is presently available in the Space Lab combustion facility will be necessary in order to make useful interferograms.

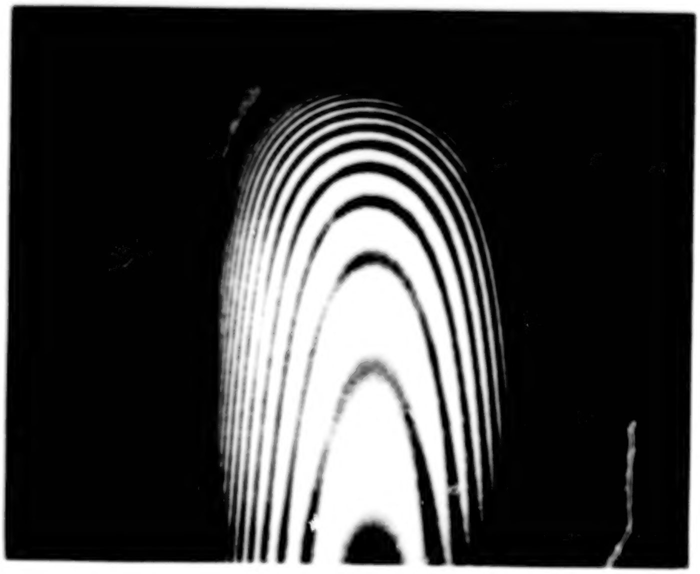
3. Publications or theses generated.

One Ph.D. thesis by David L. Reuss entitled "The Effect of Gravity on Lean Limit Flame Propagation", thesis advisor, Roger A. Strehlow, was generated under this feasibility study. Additionally, it is anticipated that this work will lead to a publication in the archival literature in the near future.

C. Conclusions

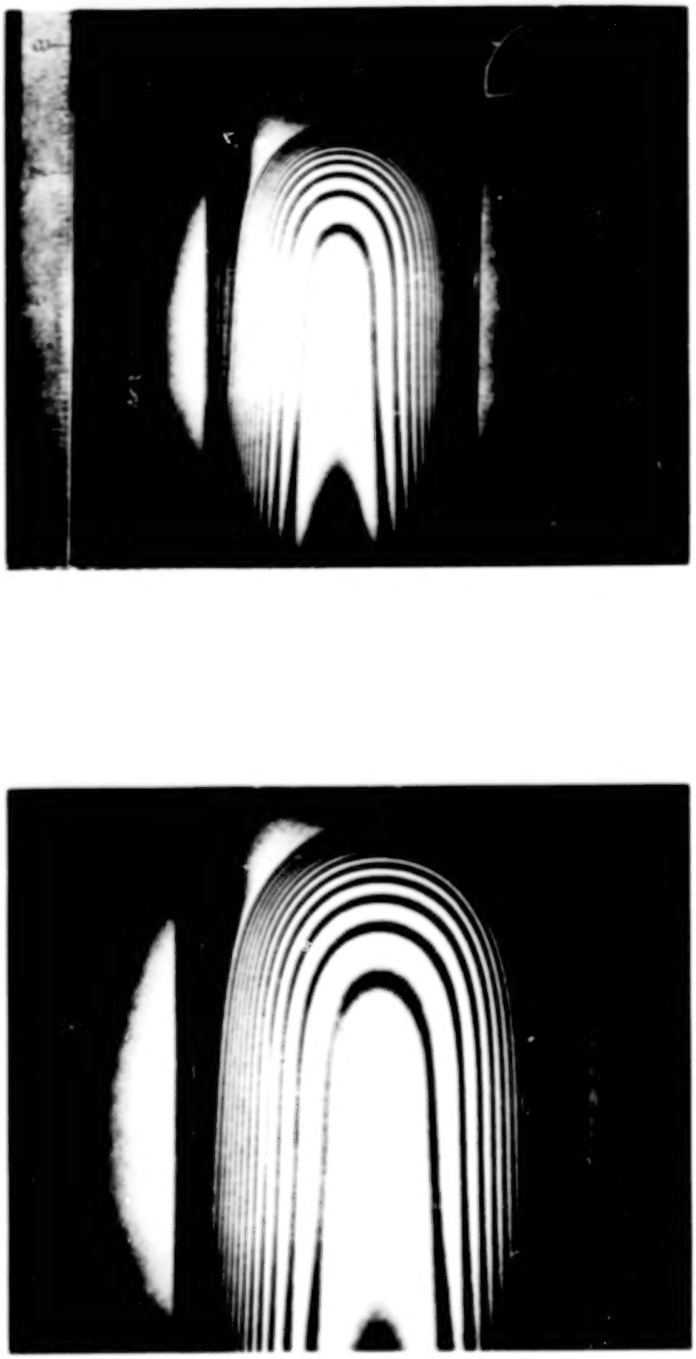
The study of the limit behavior of lean methane flames under zero g conditions and additionally, the study of the flow associated with such a flame using a laser Doppler anemometer is quite feasible in so far as the Space Lab environment is concerned. Furthermore, the length of the test time required as well as the delicacy of the instruments that must be used leads one to the conclusion that Space Lab is the only experimental tool that may be used to perform such a zero g study. The results of such a study will have a decided impact on the development of a sound theoretical model for the extinguishment of lean limit flames.





Holographic Interferograms
of Lean Limit Methane-Air Flame

Figure 7



Holographic Interferograms
of Hot Bubble After
Flame Extinguished

Figure 8

IV. CONCEPTUAL DESIGN

A. Objectives

The objectives of the Space Lab experiment using a standard flammability tube would be to:

1. Determine the lean limit of methane-air mixtures in zero gravity.
2. Measure the propagation velocity of the flames in near lean limit methane-air mixtures.
3. Measure the fluid velocity distributions associated with the flame's passage.
4. Measure the heat transfer from the flame to the wall.
5. Measure the fluid density distribution associated with the flame's passage.

The above information will yield a complete characterization of the flame system under zero g conditions. It is anticipated that the same information will be developed in the same apparatus under 1-g conditions for an upward propagating flame. The comparison of data taken in the same apparatus on the same flame system under both zero and 1-g conditions will prove to be very useful in the development of a theoretical model of the extinguishment process for lean limit flames.

B. Apparatus

Figure 3 is a plan view of the combustion facility showing the location of the LDA relative to it. Figure 9 is an elevation view of the same apparatus showing its position relative to both the flammability tube, the cameras, and the beam referencing system which is used to determine the velocity of the flame propagation, as well as the relation between the location of the visible flame and the location of the density gradients in the flame. In addition to this the following support equipment will be needed:

1. The gas supply system to prepare and introduce the combustible mixtures into the flammability tube.
2. A particle-feed system to place fine alumina particles in the test gas mixture so that LDA signals may be obtained.
3. A cathotometer-telescope for alignment.

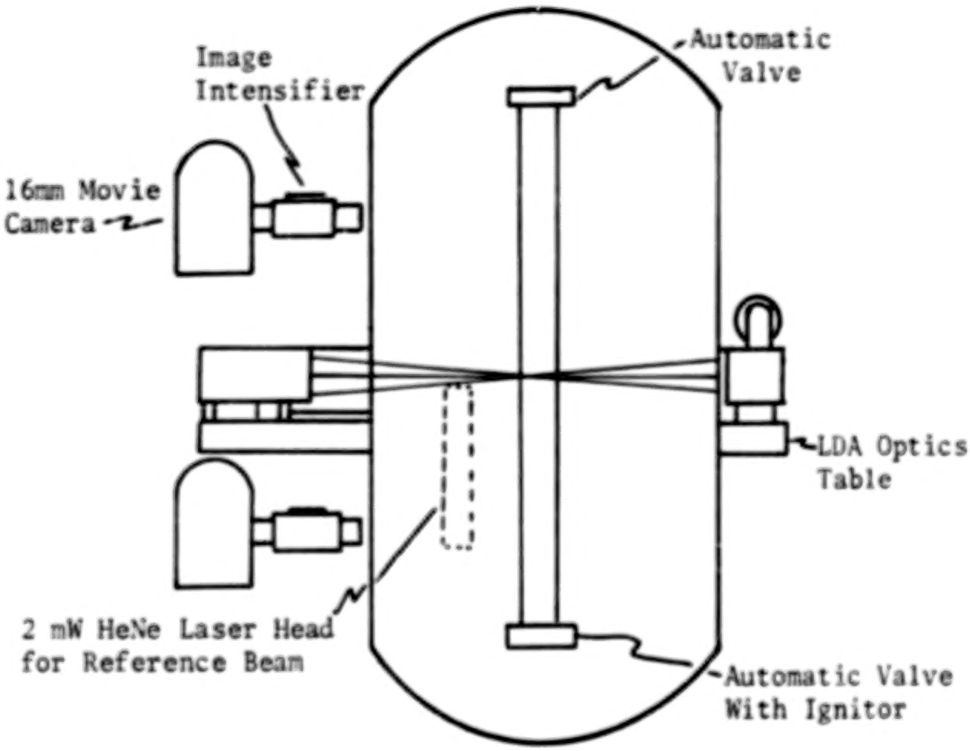


Illustration of Proposed
Experimental Equipment
Front View

Figure 9

4. A tube cleaning system (details of this have not yet been worked out).
5. A syringe system to introduce a quantity of methane near the igniter.
6. An igniter system as well as remote operating valves to place the valves in the filling and firing position.
7. Electronic support systems for the LDA and various timing circuitry needed to measure the velocity of flame propagation.

A detailed listing of suggested components to meet these requirements is included in this report as the appendix.

The gas-handling system is very important to this experiment as well as to other possible combustion experiments. There are a number of trade-offs that one must be aware of when designing the gas-handling system. First and foremost is the question of safety. By far the safest way of mixing the gases is to handle the gases as pure fluids in storage and to mix them as needed through critical flow orifices. With proper design, critical flow orifices can be used to meter a fixed composition mixture into a vessel either by flowing the mixtures through the vessel at constant pressure or by filling the vessel from zero pressure to the desired pressure. In the experiment that is being described in this report we will have to fill the vessel by displacement at constant pressure because of the need for seeding the gas. Thus, in this system we will meter air through a critical flow orifice and pass this metered air through the particle-dispersal system before mixing it with methane to make a combustible mixture. Under these circumstances the combustible mixture will exist in only a very short length of tubing and the chance for an accident involving combustion will be very slight.

It must be pointed out that it is almost impossible to mix the gases by an introduction technique where one introduces gas A and later gas B, particularly if the apparatus under question is of any size. The reason for this problem is that convective or buoyant mixing cannot occur under zero g conditions and only simple diffusion can occur. Thus, after preparing a mixture, one must either stir the mixture physically with a fan system or wait an extremely long time for normal diffusion processes to cause the mixture to reach a uniform composition. Therefore, the only viable technique is to premix the gases in a flow system and use that flow system to fill the vessel of interest. Storing the gases as a combustible mixture at high pressure is extremely dangerous and should not be done under any circumstances.

C. Measurements

The measurements that are planned are:

1. Composition of the lean flammability limit for zero g methane-air flame.
2. The speed of propagation of such a limit flame and of near limit flames in the 51 mm diameter tube.
3. The flow field associated with near limit flames in the tube.
4. Heat transfer to the wall surface.

It is anticipated that these measurements will be compared to similar measurements made for upward propagation under 1-g conditions in the same apparatus.

These comparative measurements will allow us to uniquely define the flammability limit under zero g conditions and to learn how the structure of the flame and the flow associated with the flame changes due to the effect of buoyancy forces. Heat transfer measurements will show how the gravity force affects heat losses to the wall in this particular experiment. Since it is well known that both the flows associated with the flame and the heat loss to the wall is important to the limit behavior of these flames, these pieces of information will be very important in formulating analytical description of the mechanism of extinction.

It is still considered desirable to measure the density distribution as discussed in Section III. f. Since the present combustion facility is not capable of accepting a holographic interferometer, it is hoped that a modified combustion facility will be considered in the future.

V. CONCLUSIONS

A definitive experimental study has been carried out in order to develop an understanding of the effect gravity has on lean limit flame propagation and the extinguishment process. The research conducted under this contract has demonstrated that the basic experimental apparatus needed for performing this reseach in Space Lab is feasible. The new 0-g and 1-g experimental results have added to our knowledge of the lean limit flame phenomenon and demonstrated that the effect of gravity has on the lean limit flame propagation is not as well understood as previously thought. For this

reason there is a strong justification and motivation for conducting the proposed program in the 0-g environment of the Space Lab experimental laboratory.

VI. REFERENCE

1) DeWitt, R. L., "Preliminary Concept, Specifications, the End Requirements for a Zero-Gravity Combustion Facility for Space Lab", NASA TM 78910, June 1978.

VII. APPENDIX -

DEFINITION OF HARDWARE AND SERVICES FOR SPACE LAB COMBUSTION EXPERIMENTS

Lean Limit Flammability Study

1. Kodak 2475 Recording Film: Estar-AH Base. Cat #179-3900.
2. A. A standard flammability limit tube (SFLT) with end valves. A capability for injecting 4 cc of CH_4 near the igniter wire must be included.
   B. Tube-cleaning swab, e.g., chamois.
   C. Electric igniter (nichrome wire coated with nitrocellulose).
   $12 \rightarrow 30$ VAC or VDC
   $10 \rightarrow 25$ Amps < 40 msec duration
   D. CH_4 and air metering systems.
   3 to 7% CH_4 in air, continuously variable
   E. Aluminum oxide particle-feed system with air only feed and mixing.
   F. System to mix CH_4 and particle-laden air before entering tube.
   G. Image intensifier for each camera, e.g., Javelin High Viewing Device.
   H. Flame detector reference system.
      i) 2mW HeNe laser head and power supply with 1-D translational movement, e.g., Spectra Physics 145 head, 248 power supply.
      110/115/220 VAC ±10%
      50-60 Hz single phase
      23 watts
      ii) Beam splitter optics integrated with laser.
      iii) Two beam deflection reference systems with 2-D translational and rotational adjustment. Each detector consists of a 100 μm aperture in front of a phototransistor, e.g., MRD 450.
      iv) One shielded lead from detector to each associated electronic circuit.
      v) Electronics, 10 VDC, 100 mA.
      vi) One shielded lead from electronics to data acquisition system.
   I. Product gas sampling syringes. This also requires that chromatograph carrier gas (e.g., helium) be available to sample as a control sample.

J. i) Heat transfer gage in wall of SFLT, e.g., Medtherm Film thermocouples.

ii) One shielded lead from thermocouple to amplifier.

iii) Constant temperature reference junction, e.g., Kaye Instruments Thermocouple Reference System.

117 v 60 HZ

220/240 V 50 HZ

100 watts

iv) One shielded lead from reference to amplifier (could be hard wired)

v) One differential amplifier - 1000 x

$\geq$ 200 MΩ input impedance

e.g., Teledyne/Phil Brick

requires ±150 DC 50 mA

vi) One shielded lead from amplifier to data acquisition system

Note: System must resolve 0.01°C.

K. i) Holographic Interferometer - $\geq$ 15 mW HeNe Laser

1) beam splitter

2) expansion lens and special filter assemblies

1) diffuse glass screen

1-3) front surface mirrors

1) holographic plate holder

1) electronically triggered shutter

ii) One shielded lead from flame detector electronics to shutter electronics.

iii) Kodak Type 131 high speed holographic plates, 4" x 4" (6 required) OR

Kodak high speed holographic film 50-253 (ESTAR Base), 4" x 5" sheets.

L. Laser Doppler Anemometer

i) $\geq$ 25 mw HeNe Laser

ii) Optics

a) fringe mode for longitudinal velocity component (V_z).

b) reference beam mode for radial velocity component (V_r).

iii) Two photomultiplier assemblies with power supplies and electronic amplifier.

iv) Frequency shifter with power supply and two signal mixers.

v) Two LDA Frequency Counters with a signal validation circuit and digital interface.

vi) Leads (coax cables)

a) leads to power photomultiplier tube (1 each)

b) 1 lead to power frequency shifter

c) 2 leads for signal from photomultipliers to frequency mixers (1 each)

d) 2 leads from mixers to frequency counters (1 each)

e) digital data lines from counters to data acquisition system

M. Data Acquisition System

i) One A-D converter for thermocouple

- 12 bit words
- 0 $\rightarrow$ 25 mV in 0.1 sec
- 0.2 mV resolution

ii) Two A-D converters for flame detector signals

- 12 bit words
- must resolve time of voltage spike peak to 0.5 msec. The spike rises from 0 to -10 VDC in 10 msec.

iii) Digital buses treating each counter as a device. Each counter outputs one 16-bit word and one data ready pulse. An IO data interface with buffer memory is available on TSI counters.

iv) Digital tape accepting all 5 data words simultaneously.

N. Data verification system, e.g., CRT computer terminal with graphics capability to plot stored data in order to verify successful runs.

3. The anticipated maximum total time for a burn will be less than x/3 seconds, where x is the length of the tube in centimeters. 5×10^{-4} g is acceptable for our work.

4. Since it is not obvious what to expect in these tests, it is imperative that observations be made of the combustion process. The PI could then

make sure the tests are appropriate so that slight schedule modifications could be made, e.g., what mixtures need to be looked at or redone. This would allow the PI to effectively trouble shoot any problems that might arise. The TV camera might also require an image intensifier.

5. Effluents

Compound	Molecular Wt.	State	Quantity/run % of total volume
During filling (10 tube volumes total)			
CH_4	16	gas	6
N_2	28	gas	74
O_2	32	gas	20
After burn (total fuel conversion & complete combustion)			
CH_4	16	gas	0
N_2	28	gas	74
O_2	32	gas	8
H_2O	18	gas & liquid	12 (gas)
CO_2	44	gas	6

There is a possibility that CO may be present after a burn due to incomplete combustion. An extreme maximum would be 3%. There may be less than total fuel conversion so that the after burn values may vary, i.e., less H_2O and CO_2 and much more CH_4 and O_2.

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16. Abstract
A study was conducted over a three year period in which fundamental experiments on flammability limits in a zero gravity environment were defined. Initially, the need for this research was justified on scientific, as well as, societal grounds. A feasibility study was carried out in which key aspects of a possible spacelab experiment were investigated analytically, experimentally on the bench, and in drop tower facilities. Finally, a conceptual design for a spacelab experiment was developed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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